Robust and Repeatable Automated Velocity Analysis

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Summary

Reliable and repeatable seismic velocity estimates are critical for seismic data processing. In addition, velocity estimates are used in both acoustic and elastic inversions, rock property evaluation, pressure prediction and fracture characterisation. Although the seismic velocity that is measured by a short spread of receivers at the surface is an approximation to the rock velocity, this approximation is often useful in both quantitative and qualitative analyses. However, a question arises as to how reliable the estimate is in terms of repeatability. In other words, since the measured velocity is not entirely physical, will it change dramatically if data were shot with different acquisition parameters? What about different times and/or seasons, with correspondingly different statics? While the influence of processing parameters can always be tested within a particular dataset, one is left to wonder how much the intrinsic properties of the dataset influence the result.

A robust method of seismic velocity analysis is proposed that does not use semblance and is not sensitive to variations in seismic amplitudes. Instead, the technique uses an alignment procedure that is akin to a time-variant trim static. After filtering of outliers and cycle skips, a least squares fit to the traveltimes gives the velocity. Thus although the method uses amplitudes in a sense to obtain relative time shifts between traces, it is not sensitive to AVO or time-lapse changes in the data. This method can also be used to estimate azimuthal velocity variations for wide-azimuth data by inverting the traveltimes for the appropriate offset and azimuthal variation.

The repeatability of this velocity analysis technique is demonstrated with an example from a time-lapse survey shot in the Williston Basin, Saskatchewan. In this example velocity analysis showed remarkable repeatability, despite significant variations in ground conditions and consequently refraction and reflection statics solutions.

The Velocity Analysis Methodology

The seismic data are sorted into CMP gathers within the conventional processing flow at a velocity analysis step. Generally two passes of statics and hand-picked velocities (on an 800 m grid) are applied before the automated velocity analysis. A correlation procedure is then performed which is similar to a time-variant CMP trim static; however, it also handles events that reverse polarity. This is achieved by choosing a spatial window in which data are stacked to produce a pilot trace for the cross-correlation. This spatial window is then moved across the CMP with new pilot traces being computed at each offset and correlated with the trace in the center of the window. In this way the pilot trace represents the local phase and amplitude characteristics of the data. Other methods of computing a pilot trace can be considered (such as a stack with noise cleanup) depending on the data characteristics and noise level. The technique can also be applied to pure shear or converted mode data.

Once the relative time shifts for each offset are computed they are added to the time shifts resulting from application of NMO. The resulting traveltimes are inverted for velocity using a straight line fit in the T^2-X^2 domain. Figure 1 shows an example of fitting traveltimes in this manner. Notice that cycle skips occur which can result in an erroneous traveltime pick. After an initial fit, statistical analysis is used to define outliers and they are omitted from the final inversion. The resulting algorithm is applied on a CMP by CMP basis at regular time intervals, with no information being used from adjacent CMP's. This avoids artifacts such as INLINE or XLINE smearing. In addition, since a least squares fit is performed, error analysis is straightforward and these errors can be used to discriminate poor velocity picks on an individual basis without influence from adjacent CMP's. Figure 2 shows a map of a typical example of 'raw' inverted velocities from the traveltime inversion. Also plotted are the velocity analysis locations – every 3rd ILINE and 3rd XLINE (100 m grid). Clearly some smoothing is desired to reduce the occasional spurious velocity, however, in general the inversion is extremely stable from one analysis location to another.

Using the traveltime formulation given by Grechka and Tsvankin (1998) the computed traveltimes for offsets and azimuths in a wide-azimuth 3D dataset can be inverted for an azimuthal velocity variation. This can be useful in fracture characterization, analysis of principal stress directions for shear-wave splitting and improving data quality (Williams and Jenner, 2002) and prestack data analysis such as AVO and azimuthal AVO analyses (Jenner, 2002). Figure 3 shows an example gather before and after updating with the azimuthal velocity inversion.

Robustness of Velocity Measurement

As part of the Colorado School of Mines' Reservoir Characterization Project Phase VIII study, three 9C surveys were conducted over a portion of Weyburn Field, Saskatchewan, undergoing CO_2 flooding. The first survey, in 2000, was shot one month after injection started. The second survey was shot approximately one year later over significantly different ground conditions (dry as opposed to wet). The data from the second survey were also noisier and had lower frequency content than the first survey. Although some time-lapse anomalies were postulated based on the matched migrated sections, they were noisy and difficult to draw definitive conclusions from. A third survey was shot 2 years after the baseline, this time in frozen ground conditions.

These three surveys presented an excellent opportunity to test the robustness of the velocity measurements with respect to changing survey conditions, statics, noise and differing equipment. The source and receiver positions were very similar in both cases, so the influence of survey geometry could only tested by simply reducing each survey to a subset of sources and receivers. In general the first and third surveys were of comparable quality and yielded an excellent time-lapse dataset. 4D anomalies caused by the CO_2 injection were readily apparent from the matched migrations (vertical component) between these data and the first, baseline survey.

For the purposes of investigating the robustness of the velocity inversions from one survey to another, the baseline and first monitor surveys were processed independently. This resulted in very different refraction and residual statics solutions, as well as different deconvolution operators and applied gain. In order to account for small variations in structural statics solutions and account for gross phase and amplitude spectral differences a CMP consistent matching filter was applied to the monitor survey. This ensured that the events on the monitor data would be at approximately the same two-way-traveltime and phase as the baseline so that velocities could be compared between the datasets. The filters were designed to encompass the reservoir and were computed over an 800 ms time window with 200 ms filter lengths.

Figure 4 shows an example of the inverted RMS velocities at a horizon above the reservoir where CO_2 was being injected. Clearly most of the major features in the velocity field are similar. The major differences observed in the center of the survey are where the monitor survey inversion resulted in a velocity of 2551 m/s where the baseline survey inversion was 2538 m/s, a difference of only 0.5% in the RMS velocities.

Similarly, the traveltime-inversion method resulted in traveltimes robust enough to confidently measure the azimuthal variation of NMO velocities. Figure 5 shows the inverted interval difference in velocity between the fast velocity direction and the slow velocity direction for the baseline and monitor surveys. Again, some differences exist, but the overall pattern is strikingly similar. In the azimuthal velocity computation robust inversion for the interval parameters required using a more sophisticated prestack matching process to achieve comparable levels of similarity.

Conclusions

A robust method of automatically picking velocities is presented that uses traveltime calculations, rather than semblance analysis, to invert for the stacking velocity. This has the benefit of being insensitive to AVO and amplitude noise in the data. Using time-lapse datasets shot in differing ground conditions, the method is shown to be both robust and produce repeatable automated high-density velocity analyses. This is particularly important for 4D studies where differences in amplitudes and AVO at the reservoir may have an impact on semblance-based velocity analyses.

References

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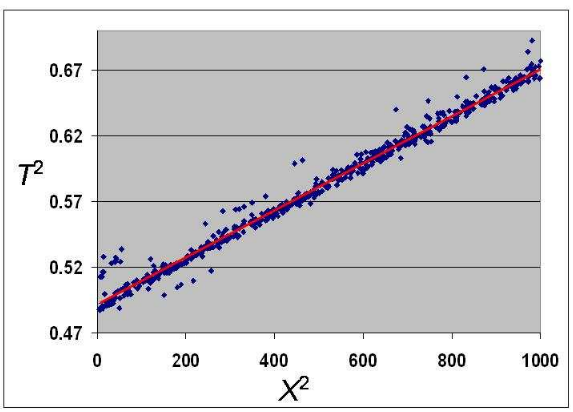

Figure 1. Example of T^2-X^2 plot obtained from computing differential time shifts for a reflection event at 0.5s Two-Way-Time. The outliers are easily defined by statistical analysis and removed before the final fitting.

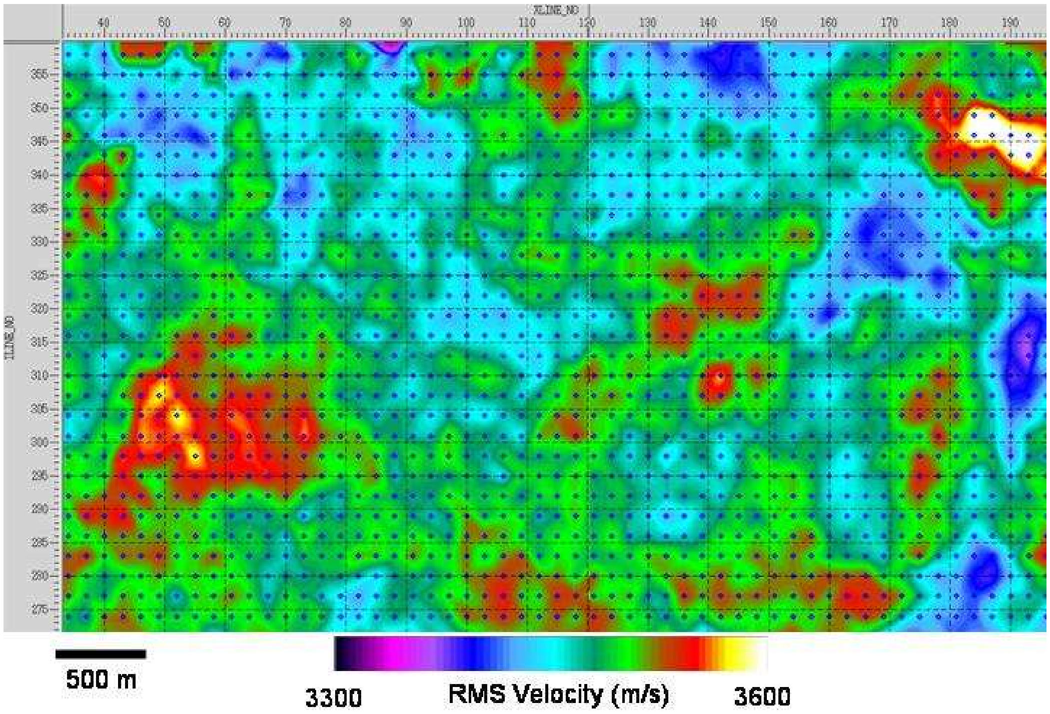

Figure 2. Time slice of velocities computed using the automated traveltime inversion. No smoothing has been applied and each blue dot represents an analysis location. No information is shared between analysis locations which are treated independently for the velocity inversion.

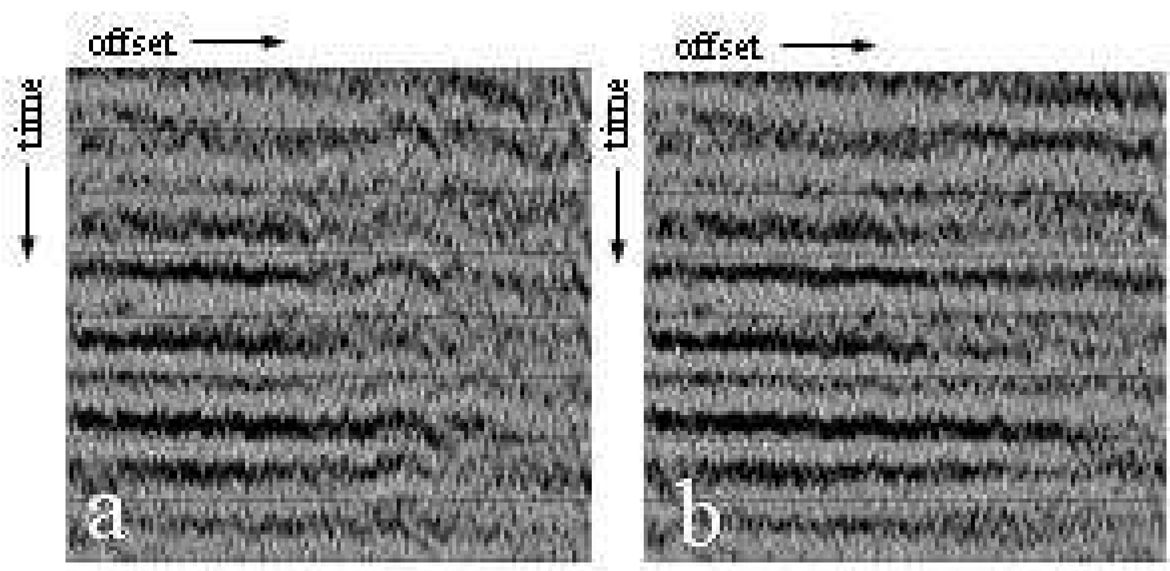

Figure 3. Example of a wide-azimuth CMP sorted as a function of offset (azimuths mixed) after processing which includes refraction and two passes of residual statics. a) best isotropic NMO correction and b) azimuthal NMO correction. The apparent anisotropy was found to be about 4% and dips in the area are less than 3º, which could account for only 0.3% of the apparent anisotropy.

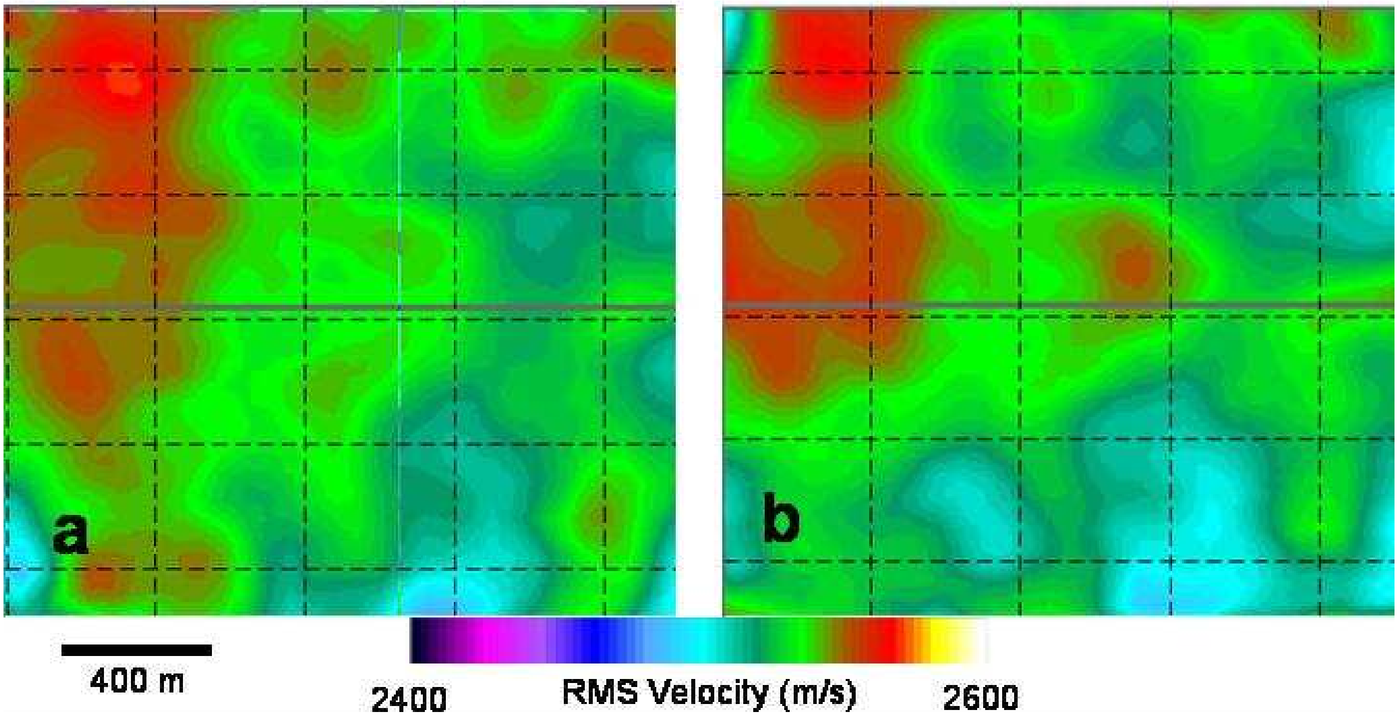

Figure 4. **Map view of velocity field computed from 2 3-D surveys shot 1 year apart. The time slice was taken from above the reservoir, so no changes are expected. The two datasets were processed independently (independent statics solutions, deconvolution and gain), with only CMP-consistent matching to allow for comparison of equivalent time slices. The maximum difference is ~20 m/s, with most differences being less than 10 m/s.**

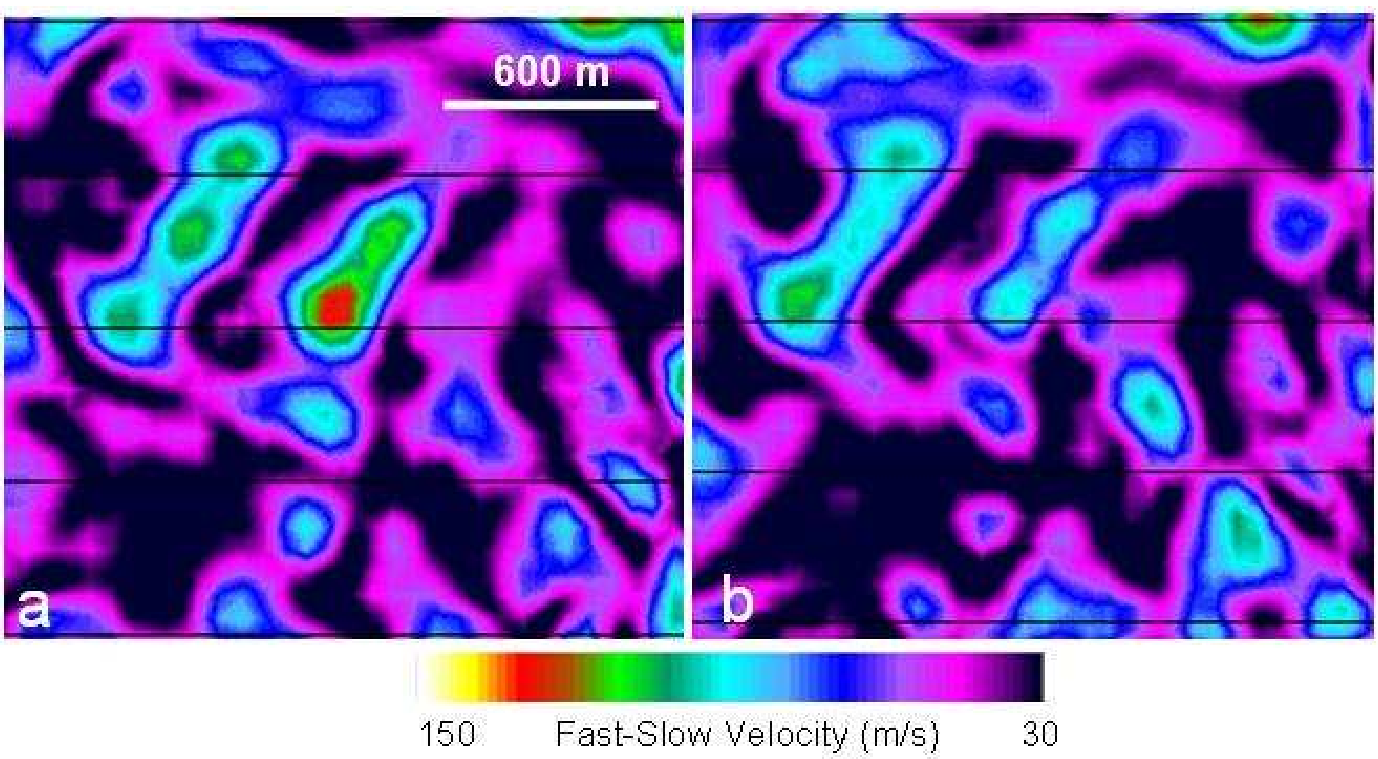

Figure 5. **Azimuthal velocity anisotropy computed from the same two surveys used in Figure 4, again with independent processing. A smaller area is shown than in Figure 4 because of the wide-azimuth requirement for azimuthal velocity inversion.**